

either event, our measurements suggest that a reinterpretation of most previous work on NH_4Cl is required.

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¹H. A. Levy and S. W. Peterson, Phys. Rev. 86, 766 (1952).

²N. Bloembergen, *Nonlinear Optics* (Benjamin, New York, 1965); R. Bersohn, Y. H. Pao, and H. L. Frisch, J. Chem. Phys. 45, 3184 (1966); S. Keilich, Acta Phys. Polon. 33, 89 (1968).

³A. Guinier, *X-Ray Diffraction* (Freeman, San Francisco, 1963), Chap. 2.

⁴I. Freund, Phys. Rev. Letters 21, 1404 (1968).

⁵I. Freund, Phys. Rev. Letters 19, 1288 (1967).

⁶These samples were prepared from reagent grade NH_4Cl that had been extensively recrystallized. The powders were obtained from solution by very slow evaporation. The very fine dendritic structures that precipitated initially were then allowed to equilibrate with a saturated solution over a period of several months. The final crystallites were very smooth and rounded and exhibited no measurable strain under the polarizing microscope.

⁷A recent thesis by P. D. Lazay (Massachusetts Institute of Technology, 1968, unpublished) contains a convenient, ~ 100 -entry bibliography. The single crystals used in our work were very kindly supplied by Dr. Lazay.

DOMAIN-WALL MOBILITY IN YTTRIUM ORTHOFERRITE

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Domain-wall mobility values from $6000 \text{ cm sec}^{-1} \text{ Oe}^{-1}$ at 300°K to $50\,000 \text{ cm sec}^{-1} \text{ Oe}^{-1}$ at 77°K , among the highest observed in insulating magnetic materials, have been measured in YFeO_3 . We have observed a monotonic temperature dependence of mobility which is qualitatively different from that found in other magnetic insulators and which we believe represents intrinsic behavior of wall mobility in YFeO_3 . Domination of wall relaxation by surface roughness has been eliminated by proper surface preparation.

We have measured domain-wall mobility values for YFeO_3 from $6000 \text{ cm sec}^{-1} \text{ Oe}^{-1}$ at room temperature to as large as $50\,000 \text{ cm sec}^{-1} \text{ Oe}^{-1}$ at 77°K . These values are among the highest reported for insulating magnetic materials¹ and exceed, by an order of magnitude or more, the values of wall mobility observed in the rare-earth orthoferrites.² The domination of wall relaxation by surface roughness, believed to figure prominently in the mobility measured in some magnetic insulators,³ has been eliminated in our measurements by proper surface preparation. The temperature dependence of mobility reported here for YFeO_3 is believed to be characteristic of the bulk material and is qualitatively different from domain wall-mobility measurements in other magnetic insulators.

YFeO_3 is a canted antiferromagnet with the easy axis for the net magnetization along the c axis of the orthorhombic crystal structure. The canting arises from an antisymmetric exchange

interaction⁴ which confines the magnetization to the a - c plane in which it sees an effective uniaxial anisotropy together with a small cubic term.⁵ The crystals were grown from a flux⁶ composed of a mixture of PbO and B_2O_3 . The total impurity level, except for Pb , was shown by mass-spectrographic analysis to be less than 20 ppm.⁷ For YFeO_3 grown by this method, one can expect almost 0.3% by weight of Pb to go into the lattice, replacing yttrium ions.⁸ The samples were cut into plates normal to the c axis and polished with diamond powder, in steps of decreasing grit size, to a thickness of about $150 \mu\text{m}$. The last step was accomplished with diamond particle sizes not larger than $1 \mu\text{m}$.

One sample, hereafter referred to as sample A, received further surface treatment consisting of mechanical polishing on a very fine scale in combination with chemical polishing. After final polishing, sample A had a thickness of about $50 \mu\text{m}$ and a coercive force for domain-wall motion

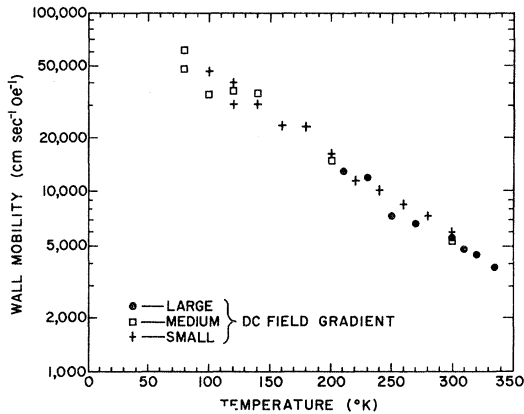


FIG. 1. Temperature dependence of wall mobility in YFeO_3 , sample A, measured at different strengths of dc field gradient.

of less than 0.1 Oe. The temperature dependence of domain-wall mobility measured on sample A is given in Fig. 1. The wall mobility is determined using a previously described method involving the measurement of the frequency response of a single domain wall driven sinusoidally about a static equilibrium position fixed by a dc magnetic field gradient.² The use of different strengths of dc field gradient in obtaining the data given in Fig. 1 leads to a further verification of the validity of the simple relaxation model described in Ref. 2, since the mobilities are seen to be independent of the field-gradient magnitude. Field gradients of 1080, 1820, and 2855 Oe/cm were used at 300°K with gradients about half again as large but in the same proportion at the lowest temperatures.

Mobility values measured on two other samples grown in the same manner as sample A but from a different batch are given in Fig. 2, together with the values measured on sample A for comparison. Sample B underwent the same final surface processing as did sample A. Sample C was polished all the way to a 50- μm thickness using 1- μm diamond powder, but this left the sample with a coercivity too high and too nonuniform to permit measurement of mobility with the oscillating-wall technique. However, a 15-h anneal at 1500°C in an oxygen atmosphere brought the coercivity of sample C down to about 0.1 Oe so that the mobility data given for that sample in Fig. 2 could be measured. This high-temperature anneal removes the elastic and plastic strain introduced in rough polishing.⁹

Previously reported room-temperature values of wall mobility for YFeO_3 , measured on a single-crystal platelet obtained directly from the melt²

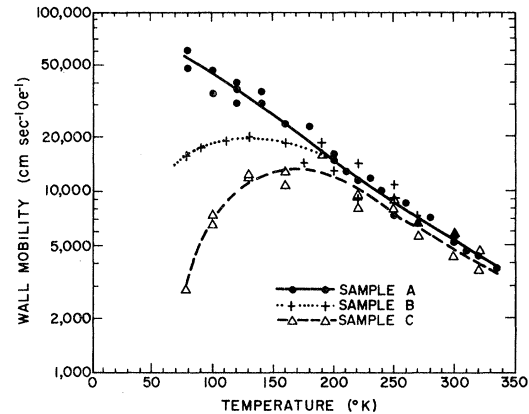


FIG. 2. Temperature dependence of mobility measured in three samples of YFeO_3 . See text for differences in their preparation.

and deduced from wall-velocity measurements¹⁰ on a large chemically polished single crystal with a coercive force of about 5 Oe, are nearly an order of magnitude lower than the values reported here. In the neighborhood of 130°K the earlier values are about three orders of magnitude lower than the present measurements indicate. The conclusion that the present measured wall mobility is dominated by relaxation mechanisms in the bulk crystal rather than by mechanisms involving surface roughness is based upon two observations. One is the essentially identical behavior of mobility with temperature observed in all three samples above about 180°K despite a difference in surface preparation. The other is that the temperature dependence of the measured mobility is inconsistent with surface roughness as the dominant wall-relaxation mechanism. The temperature-dependent magnetization¹¹ would cause a reduction, with increasing temperature, in the strength of local demagnetizing energy associated with surface roughness which implies³ a mobility that would grow with temperature. A parallel can be drawn with the behavior of ferromagnetic-resonance linewidth in yttrium iron garnet (YIG). There it was shown that surface roughness makes a linewidth contribution which is additive to those of other relaxation mechanisms¹² and which, having the temperature dependence of the magnetization¹³ at applied fields $\gg 4\pi M$, gives very good agreement with the behavior of linewidth measured¹² in highly purified YIG when added to other known relaxation processes.

In terms of bulk-crystal properties, wall mobility generally varies with temperature not only as a result of temperature-dependent relaxation

mechanisms but also as a result of a temperature-dependent wall width which is proportional to the square root of the ratio of exchange to anisotropy energies. In fact Gyorgy and Hagedorn,¹⁴ upon application of the Gilbert equation of motion, have shown specifically for YFeO_3 at low fields that mobility is given by $\mu_B = \gamma\alpha^{-1}(A/K)^{1/2}$ for a Bloch wall parallel to the a - c plane and $\mu_N = \gamma\alpha^{-1}[A/(K + 2\pi M^2)]^{1/2}$ for a Néel wall parallel to the b - c plane. Here γ is the magnitude of the gyromagnetic ratio, α is the phenomenological Gilbert damping parameter, A is the isotropic exchange constant, and K is the effective uniaxial anisotropy acting on the net magnetization in the a - c plane. Since $K \gg 2\pi M^2$ in YFeO_3 , then $\mu_B \approx \mu_N$. In YFeO_3 , however, domain-wall energy, which is proportional to $(AK)^{1/2}$, has been shown¹⁵ to be nearly temperature independent between 77 and 350°K. Since A can be taken to be independent of temperature,^{5,16} the rather strong temperature dependence observed for μ in the present measurements cannot be attributed to the behavior of the anisotropy but must be attributed to temperature-dependent relaxation mechanisms incorporated in α .

The results of these measurements are unique in that, to our knowledge, only in YFeO_3 does the wall mobility grow rapidly with decreasing temperature while at the same time reflecting directly the temperature dependence of the relaxation processes involved. Although mobility was observed to increase² at lower temperatures in EuFeO_3 and TmFeO_3 , its behavior in these materials is influenced by temperature-dependent wall widths. It is suggested that the wall mobility reported for sample A, particularly above 180°K, represents the intrinsic wall mobility in YFeO_3 . The origin of the differences in the behavior of mobility among the samples at the lowest temperatures is not certain. There is strong evidence⁸ that Pb goes into the lattice with a compensation mechanism involving the replacement of Y^{+3} with Pb^{+2} accompanied with a change in valence of Fe^{+3} to Fe^{+4} . The presence of Fe in the two ionization states introduces the possibility of a relaxation mechanism involving electron hopping¹⁷ which may be operative at the lower temperatures and which would be dependent upon Fe^{+4} concentration.

There is an important parallel between the study of wall mobility in the orthoferrites and the study of ferromagnetic-resonance linewidth in the rare-earth and yttrium iron garnets. In

highly purified YIG, the linewidth is extremely narrow and grows with increasing temperature,¹² reflecting the temperature dependence of the Kasuya-LeCraw relaxation mechanism.¹³ From the temperature dependence of the linewidth in YIG doped with small concentrations of rare-earth ions, Dillon¹⁸ was able to study the relaxation properties of the rare-earth ions through their exchange coupling with the magnetization of the iron ions. In the orthoferrite system where resonance for linewidth study does not occur at convenient microwave frequencies, relaxation properties of the rare-earth ions may be similarly studied from measurements of wall mobility in YFeO_3 in which small fractions of the Y^{+3} ions have been replaced by rare-earth ions.

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¹For wall mobility in yttrium iron garnet, see M. A. Wanas, *J. Appl. Phys.* **38**, 1019 (1967); F. B. Hagedorn and E. M. Gyorgy, *J. Appl. Phys. Suppl.* **32**, 282S (1961). For mobility in various of the ferrites, see E. Steinbeiss, *Phys. Status Solidi* **18**, 241 (1966); J. F. Dillon, Jr., and H. E. Earl, Jr., *J. Appl. Phys.* **30**, 202 (1959); J. K. Galt, *Bell System Tech. J.* **33**, 1023 (1954).

²F. C. Rossol, *J. Appl. Phys.* **40**, 1082 (1969).

³H.-L. Huang, *J. Appl. Phys.* **40**, 855 (1969).

⁴D. Treves, *Phys. Rev.* **125**, 1843 (1962).

⁵G. Gorodetsky, S. Shtrikman, Y. Tenenbaum, and D. Treves, *Phys. Rev.* **181**, 823 (1969).

⁶J. P. Remeika, unpublished.

⁷J. P. Remeika, private communication.

⁸J. P. Remeika and T. Y. Kometani, *Mat. Res. Bull.* **3**, 895 (1968).

⁹E. Heinlein and R. D. Pierce, to be published.

¹⁰H. Umabayashi and Y. Ishikawa, *J. Phys. Soc. Japan* **20**, 2193 (1965).

¹¹G. Gorodetsky and D. Treves, in *Proceedings of the International Conference on Magnetism, Nottingham, England, 1964* (The Institute of Physics and the Physical Society, London, 1965), p. 606.

¹²E. G. Spencer, R. C. LeCraw, and A. M. Clogston, *Phys. Rev. Letters* **3**, 32 (1959).

¹³M. Sparks, *Ferromagnetic-Relaxation Theory* (McGraw-Hill, New York, 1964), p. 161.

¹⁴E. M. Gyorgy and F. B. Hagedorn, *J. Appl. Phys.* **39**, 88 (1968).

¹⁵F. C. Rossol, *IEEE Trans. Mag.* **5**, 562 (1969).

¹⁶G. Gorodetsky, *J. Phys. Chem. Solids* **30**, 1745 (1969).

¹⁷J. K. Galt, *Bell System Tech. J.* **33**, 1023 (1954).

¹⁸J. F. Dillon, Jr., *Phys. Rev.* **127**, 1495 (1962).